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VORTEX MODELING

Annual Progress Report

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Arctic and Earth Sciences Division
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A full numerical model of the typhoon with rigid constraints on the divergence, vorticity and surface pressure fields was tested and found capable of producing realistic forecasts of typhoon development. The constraints on these fields are that the fields are subject to Laplace's equation in both spiral and circular cylindrical coordinates. The zero Laplacian constraint is compatible with a full scale model of the typhoon. Experiments on the role of the Richardson number, critical enstrophy and

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eddy viscosity show their necessity in the creation and maintenance of the separate typhoon regimes. The asymmetric contributions account for the major portion of the divergence and vorticity budgets. New numerical techniques which bypass finite differencing account for significant reduction in storage requirements and in computational time.

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TABLE OF CONTENTS

1. INTRODUCTION

This report to the Office of Naval Research documents results of ongoing research in the numerical modeling of typhoons. The model, in the form of the zero Laplacian vortex, has been documented both theoretically and numerically in three previous reports. This document reports on the numerical experiments with the model.

The primary finding of this report is that a complete numerical model of the typhoon runs and produces realistic forecasts of typhoon development under the constraint that the divergence, vorticity and surface pressure fields satisfy Laplace's equation in a piecewise manner. The typhoon spontaneously divides into multiple regimes given certain Richardson number constraints. Within each of these regimes the divergence and vorticity, given by $\delta = \nabla_2 \cdot \underset{\sim}{U}$, $\zeta = \underset{\sim}{k} \cdot \nabla_2 \times \underset{\sim}{U}$ respectively, and the surface pressure, p, all either maintain or develop the property of being subject to Laplace's equation. This is critically important in that the implication appears to be that the two-dimensional diffusion terms, $\gamma \nabla_2^2 \delta$, etc., for the various equations are indeed the <u>governing</u> terms in the prognostic equation.

It is not enough that the divergence, vorticity and pressure satisfy Laplace's equation. It is important to know why. The conventional wisdom had been that these terms, being zero, were immaterial and hence were dropped from consideration due to order of magnitude considerations. If, however, the fields are non-zero which satisfy Laplace's equation, and the coefficient of eddy viscosity, ν, is nontrivial, then the fields must satisfy certain criteria of spatial distribution. These distributions include spiral configurations from solutions of Laplace's equation in spiral coordinates, (Nicholson 1980), and therefore have ramifications for virtually every other term in the prognostic divergence, vorticity and pressure tendency equations.

In summary, therefore, the hypothesis underlying the zero Laplacian vortex is compatible with a fully operational numerical model of the typhoon, and, at least from this standpoint, appears to be a valid conceptual framework for understanding the unifying principle of vortex structure.

Consequently, the roles of the Richardson number, parameterized in a bulk aerodynamic sense, the enstrophy and the coefficient of eddy viscosity are of critical importance in determining the creation and maintenance of regimes in the vortex, providing the framework for the zero Laplacian criterion.

The secondary finding of these experiments, discussed in greater detail in the appendix, is that the value of the Richardson number is critically important for establishment and prediction of a regime. Not only is the value of the Richardson number important, but, so too is the time history of the Richardson number of a parcel spiralling into the center of the storm. The Richardson number falls for a parcel moving toward the center of the storm from the outer regime while the vorticity increases very slowly. Upon bottoming out at approximately 0.25 with minor oscillations, a new inner regime is maintained in which vorticity increases rapidly toward the center of the storm. As the parcel moves further inward, if the Richardson number begins to rise again, the eye or core regime begins to form. Further development of the eye prohibits further penetration by this or subsequent parcels. Preliminary results indicate that the establishment of the regime appears predictable by the behavior of the Richardson number, which precedes in time a change in the spatial distribution of the vorticity, the criterion for regime definition.

Other experiments indicate that a high coefficient of eddy viscosity in the model is essential for the governing behavior of the Richardson number and its usefulness as a predictor of regime formation.

Other results of significance are:

1) The asymmetric contributions to the divergence and vorticity budget

1) The asymmetric contributions to the divergence and vorticity budget were tested and found to be important enough to contribute up to 60% or more of the mechanism for importing and maintaining vorticity and divergence singularities in the storm.

2) Finite differencing bypasses were tested in the prediction of fields subject to Laplace's equation and found to be useful in significantly shortening computational time and storage requirements. In some instances the storage requirements were nearly halved, from 83K to 45K.

3) Subsidiary experiments were performed on the importance of the diffusive term in the pressure tendency equation. It was found that inclusion of this term is a factor in stabilizing the vortex.

Each of these experiments will be discussed in greater detail below.

2. EXPERIMENTS

The relative contributions of the symmetric and the asymmetric portions of the typhoon have been a matter of concern to the weather scientist interested in such phenomena for the following reasons. No typhoon exists without spiral asymmetries, nor do other significant atmospheric vortices ranging in size from great Pacific extratropical storms all the way down to tornadoes and waterspouts. Indeed, Golden (1974) has stated that the presence of asymmetries in the form of spiral rain bands in the waterspout appears to be the sine qua non for intensification. Not every waterspout with spiral rainbands was intense, but no waterspout which was intense was without them. Moreover, no model to date has incorporated spiral asymmetries in a numerical model of the typhoon (Trout, 1979).

For the initial experiments the model has been set up so that the fields of divergence, vorticity and surface pressure satisfy Laplace's equation in a piecewise manner in two distinct but overlapping coordinate systems. These systems, cylindrical and log spiral are documented more fully in Nicholson (1980). As stated above, when the internal values of the boundaries are set, i.e., the fields of divergence, vorticity and surface pressure satisfying Laplace's equation are themselves the forcing function of the other fields of the typhoon, the typhoon achieves steady state. Given a high enough coefficient of eddy viscosity, the Richardson number becomes a governing function for the detrmination of regimes and the fields continue to satisfy Laplace's equation in a piecewise manner. At this point they no longer operate as forcing fields but rather as a rest state of the fluid despite the myriad of other processes occuring in the lifespan of the typhoon.

More extensive samples of the critical conditions for the spontaneous maintenance of separate regimes satisfying these basic criteria are given below.

2.1 SPIRAL DIVERGENCE BANDS IN THE TYPHOON

The numerical model of the typhoon was parameterized with spiral divergence bands resulting in cloudiness and precipitation. Wave numbers one and two were tested both separately and together. It was found that 80% of the contribution

of the asymmetric portin of the divergence and vorticity budgets to a successfully operating typhoon can be accounted for by the first two wave numbers with rapidly diminishing results for higher wave numbers. The presence of the bands is the sine qua non for explosive deepening of the typhoon since they act as the chief conduit of water vapor and latent heat into the hot towers around the eye. The solenoidal term in the vorticity equation is greatly enhanced by their presence. The vorticity field, however, behaves in a forced way in response to asymmetric parameterizations of the divergence field due chiefly to the action of the divergence asymmetry in the prognostic vorticity equation

$$\frac{\partial \zeta}{\partial t} = + \ldots -\delta(\zeta + f) + \ldots$$

Further documentation of experimental results including illustrations of the vorticity field will be presented in the Appendix.

When the situation is reversed, however, the divergence field is far less likely to respond to asymmetries in the vorticity field. The axially symmetric divergence field, however, is highly dependent upon the axially symmetric vorticity distribution, and appears to be governed by it in part. This appears to be due to the term in the divergence equation

$$\frac{\partial \delta}{\partial t} = - k \cdot \underset{\sim}{U} \times \nabla\zeta + \ldots \qquad .$$

The pressure asymmetries appear as a result of the divergence asymmetries and the consequent hypsometric effects of the asymmetric release of latent heat. This in turn leads to an asymmetric solenoidal field with a consequent asymmetric vorticity field. The vorticity field seems to lag the divergence field by $\pi/2$ radians.

2.2 THE ROLE OF THE RICHARDSON NUMBER AND CRITICAL ENSTROPHY IN THE FORMULATION OF THE TYPHOON REGIMES

As the typhoon develops in response to the asymmetric divergence field an inversion begins to appear in the outer storm, suppressing axially symmetric convection. This inversion works its way in toward the center of the storm and

would ultimately choke it off completely. Were it not for the fact that the import of vorticity (due in part to the suppression of vertical velocity) causes the atmosphere to depart from what appears to be a quasi-laminar state to a quasi-turbulent state, this new state would destroy the inversion near the center of the storm, and would not permit concentrated, axially symmetric convection in the throat of the typhoon.

Upon reflection, it is evident that, if it were not for the presence of the asymmetries which allow convection in spite of the presence of the inversion, in the outer storm there would not be enough convection to sustain the storm. This is due, in part, to the weakening of the inversion by the asymmetries in the vorticity field, which cuases local wind increases in turn lowering the value of the Richardson number. The Richardson number is seen to hover about 0.25 before the onset of quasi-turbulence which destroys the inversion which in turn suppresses the vertical velocity.

Details of the experiments, including graphs of the Richardson number for both symmetric and asymmetric cases, including spiral bands, are also presented in the Appendix.

Critical Enstrophy

Due in part to the suppression of vertical velocity prohibiting the export of vorticity by the term

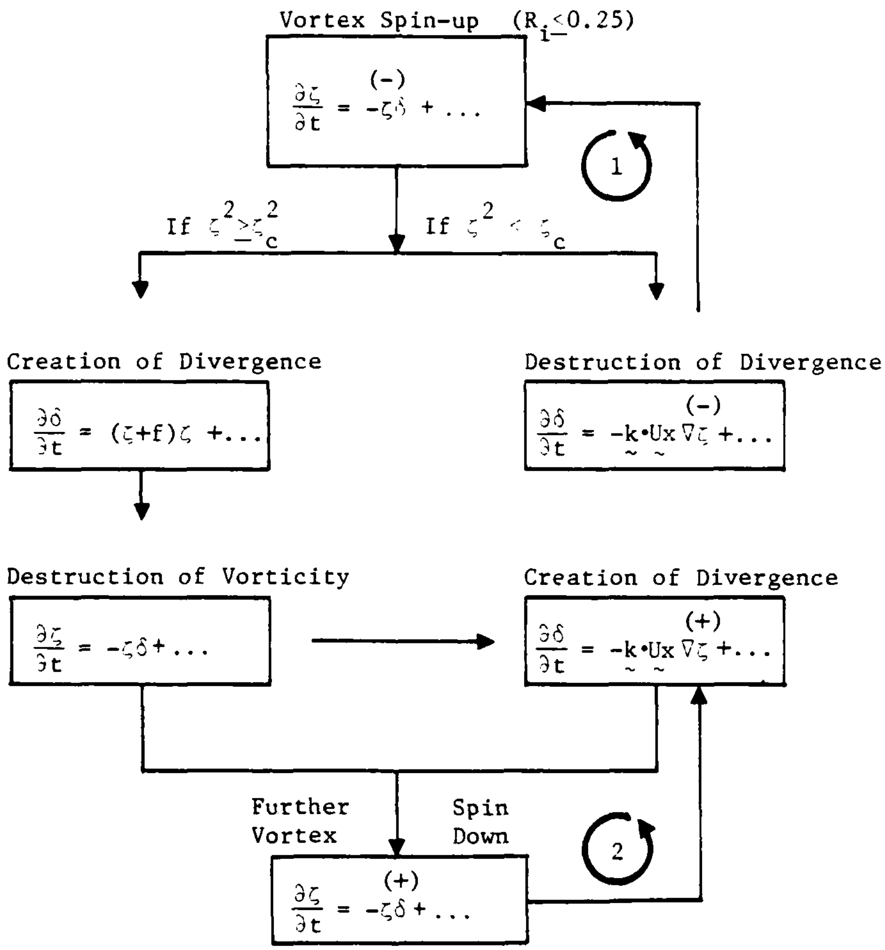
$$\frac{\partial \zeta}{\partial t} = - w \frac{\partial \zeta}{\partial z} + \ldots$$

in the vorticity equation, vorticity is concentrated in the center of the typhoon. There comes a point, however, when the feedback into the divergence equation by the presence of vorticity causes a maximum allowable concentration of vorticity. This is shown graphically in Table 2-1 which presents a very complicated procedure in simplified form.

The first box, vortex spin-up, occurs most rapidly when the Richardson number, roughly the ratio of a stability parameter to the kinetic energy of the wind field, falls below the critical value of 0.25. This occurs in the spiral bands outside the inner regime and everywhere within the inner regime that is defined by the critical Richardson number. When enough vorticity is generated so that the left hand path is chosen rather than the right hand path, the feedback loop 1 is no longer operative. Divergence is created, vorticity destroyed in the center of the storm, and the gradient of vorticity is reversed, causing the storm center to enter loop 2. By this loop, both divergence and vorticity are simultaneously destroyed in the storm center resulting in the calm, "cloud-free" windless eye. The flow chart is considerably simplified. One should bear in mind that the vorticity is constrained to be in a logarithmic distribution in the axially symmetric case by Laplace's equation. Moreover, the contributions of the asymmetries are not made explicit here due to their complexity. Maximum values of these quantities are determined in the Appendix.

TABLE 2-1

Divergence-Vorticity Budget Flow Chart
For Creation of Core Regime



2.3 FINITE DIFFERENCING BYPASSES AND PREDICTION OF BOUNDARY VALUES OF DIVERGENCE AND VORTICITY REGIMES

The question of appropriate finite differencing arises for fields which satisfy Laplace's equation in a piecewise manner. Finite differencing is necessary in the model to the extent that some of the prognostic fields such as water vapor, temperature, both actual and potential, geopotential height and certain derivative fields such as heat and water vapor flux from the sea, irrotational and nondivergent winds and air-sea momentum transfer do not satisfy Laplace's equation but remain an integral consideration of the storm processes. There are other fields, however, which do, at least initially, satisfy Laplace's equation. The experiments in this regard were designed to see if they maintained this constraint after subjection to the physical processes in the model. The experiments also examined the effect of finite differencing across boundaries which theoretically are first order discontinuities, and the substitution of boundary values for the prognosis of the total field.

When the constraint associated with the Richardson number was made explicit in the parameterization so that vertical velocity was suppressed for $R_i \geq 0.25$, the boundary between the inner regime and the outer regime became quite distinct, approaching a mathematical discontinuity. This was so even in the case of rather high coefficients of eddy diffusion, e.g., $K_{H_2} = 15 \times 10^{15} cm^2 \, sec^{-1}$. Furthermore, if an upper limit were set to the vorticity value, then the core regime and inner and outer spiral regimes maintained their distinct boundaries as well. This is just the opposite of the experiments in the preceeding section in that the boundaries and their values were assigned and the convergence of the Richardson number and maximum value of enstrophy were ascertained. In these experiments the Richardson number is set and the boundaries were allowed to vary, wander or even disappear.

In the first set of experiments the divergence and vorticity values were treated as forcing functions, with field values determined by the boundary conditions. Even though the boundary values were allowed to vary in keeping with other typhoon modelling budgets, the interior field values were held slave to the boundaries and determined as mathematical functions of these boundaries.

In the second set of experiments the field values were allowed to vary with input into the boundaries. The conformity of the field values to their mathematical predictions was used to assess the maintenance of the zero Laplacian conditions.

The criterion for conformity is discussed below:

The standard error of estimate, defined by $S_{y,x} = \sqrt{\frac{\Sigma (y - y_{est})^2}{N}}$, where

y is the field variable predicted by the numerical model, y_{est}, the analytical variable for the same field, x, based on the internal boundary values and the level in the typhoon, and N is the number of gridpoints, shows a bimodal distribution. When the coefficient of eddy viscosity is weak, then the dependence upon the Richardson number, or critical enstrophy is weak, and the standard error grows large and becomes of the order of the field value predicted in the initial state. An example of the winds at salient points in the typhoon, for a poor resolution case are given below:

<u>Wind Field</u> 900 mb, 36 hours

Rotational	$S_{y,x}$	Irrotational	$S_{y,x}$
Max			
70 m/s	55 m/s	10 m/s	4 m/s
Core			
10 m/s	7 m/s	6 m/s	3 m/s
Inner			
60 m/s	43 m/s	20 m/s	18 m/s
Outer			
30 m/s	12 m/s	3 m/s	3 m/s
Inner Spiral (Wave #'s 1 & 2)			
15 m/s	7 m/s	3 m/s	1 m/s
Outer Spiral (Wave #'s 1 & 2)			
6 m/s	3 m/s	2 m/s	0.3 m/s

The incorporation of strong eddy viscosity and consequent strong dependence upon the behavior of the Richardson number and critical enstrophy, changes this situation to a very favorable one.

<u>Wind Field 900 mb, 36 hours</u>

Rotational Maximum	$S_{y,x}$	Irrotational	$S_{y,x}$
85 m/s	4 m/s	15 m/s	0.3 m/s
Core			
7 m/s	0.2 m/s	4 m/s	0.1 m/s
Inner			
70 m/s	3 m/s	12 m/s	1.2 m/s
Outer			
40 m/s	2 m/s	9 m/s	0.4 m/s
Inner Spiral (Wave #'s 1 & 2)			
15 m/s	1 m/s	6 m/s	0.2 m/s
Outer Spiral (Wave #'s 1 & 2)			
7 m/s	0.3 m/s	2 m/s	0.03 m/s

It should be pointed out that the exact causal relationship of the Richardson number behavior to the establishment and prediction of regime formation is yet to be unequivocally determined.

Boundary Criteria

Over and above the conformity of the numerical results to predicted values within the regimes, the boundaries of the regimes themselves were studied. The maintenance of first order discontinuities in the divergence and vorticity field was used as a boundary criterion. The situation tended to be bimodal. Either the discontinuities were pronounced and the hurricane maintained its integrity, or they were amorphous, in which case the hurricane began to lose integrity by loss of the regime identities. The maintenance of regime identities appears to be the sine qua non for hurricane sustenance. This bimodality appeared quite pronounced and may represent a critical configuration of values and their combinations necessary to sustain the hurricane.

There was a certain amount of internal oscillation in the storm, possibly due to the presence of storm generated Lamb waves. When the field values departed from being 70% of the prescribed static mathematical figure as an overall whole the storm could not maintain its regime identity and quickly lost structure and began to weaken. The Lamb waves appeared most dramatically in the divergence fields which were used to ascertain the 70% criterion. The vorticity criterion was more of the order of 76%.

A surprising result was that the dissipative quality one would associate with the diffusion terms, e.g., $\nu\nabla_2^2\delta$, $\nu\nabla_2^2\zeta$, $\nu\nabla_2^2 P$, did far more to maintain the integrity of the respective regimes than to tear them down. In fact, the regimes collapsed when the coefficient of eddy viscosity was reduced by an order of magnitude due to the creation of spurious waves and random hot towers or convective maxima which bled both divergence and vorticity from the central structure.

Preliminary tests of prediction of selected fields by means of their boundary values have been performed and show promise. These fields are piecewise continuous. The pieces satisfy Laplace's equation so that the boundary values completely specify the interior values of the fields. Use of the prognostic divergence and vorticity equations in forecasting these fields thus encounters a dilemma when done by a finite difference approximation. The dilemma involves the inability of finite differencing to assess gradients across first order discontinuities for such terms as $-\underset{\sim}{U}\cdot\nabla\zeta$ and $\nu\nabla^2\delta$.

Two possibilities present themselves. The modeller may ignore the terms, hoping they will go away, with the possibility of overlooking a real physical process at the boundaries, or he may take a weighted mean of the gradients approached from either side of the discontinuity.

Both approaches were tried. Neglect of the terms at the boundaries was found to impede the development of the storm. This was rectified by inclusion of the weighted gradients. The weighted gradients, however, seemed to be accompanied by a host of unusual side effects. The weighted gradients brought about sporatic fluctuations in values at the boundaries, possibly

indicative of turbulent fluxes of divergence and vorticity between regimes. This phenomenon will be studied in greater detail in further work.

These tests imply that the discontinuities are not true mathematical first order discontinuities, nor should they be treated as such. What appears to be a discontinuity is a subscale transition zone and needs to be modelled as such.

The bright spot in the use of field values as predictors is that computational time is cut down by as much as 40% and storage by as much as 45% over an otherwise implicit nested gridding of divergence, vorticity and surface pressure values. The efficiency introduced as a result of implicit nesting also provides an excellent focus on the thermodynamic processes of the "throat" of the typhoon.

3. CONCLUSION

In spite of the optimistic results of the experiments which are documented in greater detail in the Appendix, it is important to note that this approach is sufficiently new that a great deal more checking and work needs to be done. The results are preliminary only. Further, conclusions on the validity of the experimental procedures and results must necessarily await further and more extensive testing.

APPENDIX A

A-1. THE ROLE OF ASYMMETRIC CONTRIBUTIONS TO THE DIVERGENCE AND VORTICITY BUDGETS OF THE NUMERICAL MODEL OF THE TYPHOON

Five relevant experiments are documented with various spiral waves and their combinations in the typhoon. The experiments address the forcing by the divergence field of the other fields in the typhoon, and hence contain the prefix "D". The experiments are labeled DØ, D1, D2, D3 and D4 respectively. DØ is chosen to represent the divergence forcing of the axially symmetric typhoon. D1 represents an addition of wave number one in spiral space. D2 represents the addition of wave number two, but not one. D3 represents waves one and two added to the symmetric typhoon, and D4 represents the symmetric typhoon plus waves 1 through 5.

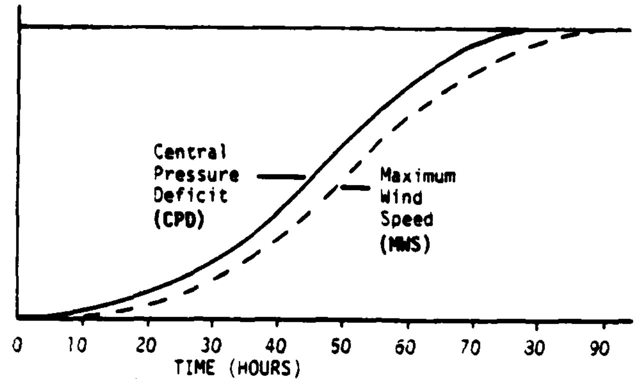
The development of the typhoon is indicated both by the central pressure deficit, CPD indicated by the solid line, and by the maximum wind speed, indicated by the dashed line. Both are nondimensional plots vs. time.

In DØ, axial symmetry only, it can be seen that it takes the typhoon 72 hours in order to reach its lowest central pressure, certainly not explosive deepening, especially in the initial stages. The typhoon was initiated with a central pressure deficit of 30 mb, and a wind speed of 30 ms^{-1}. The maximum pressure deficit was 95 mb and maximum wind 80 ms^{-1}. The wind maximum responded even more slowly than the pressure deficit, taking 86 hours to reach full potential. The addition of wave number one in D1 approximately halved the time necessary to achieve the maxima with a rapid initial deepening and an acceleration in the wind speed increase occurring noticably at 18 hours. The substitution of wave number two in D2 had less impressive results in the drop in central pressure than number one, but at 30 hours the wind accelerated markedly reaching maximum strength in a little less than 38 hours.

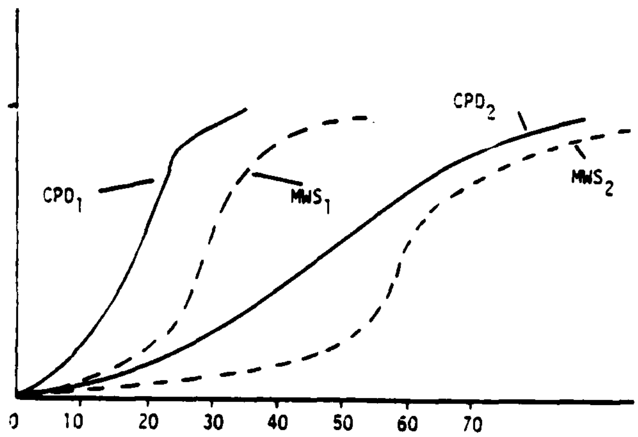
The addition of waves one and two in D3 caused rapid deepening almost at once and an acceleration in the wind field just as dramatic four hours later. Seventy-five percent of the pressure drop occurred within 8 hours and 60% of the wind intensification.

PLOTS OF CENTRAL PRESSURE DEFICIT AND MAXIMUM WIND SPEED

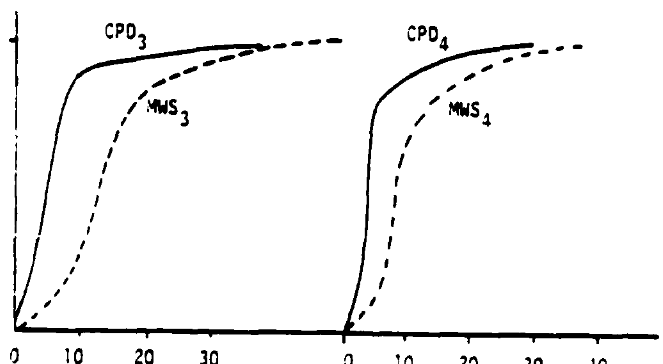
MWS vs. TIME



D0 (Axial Symmetry)



D1, D2 (Wave #'s 1, 2 respectively)



Waves 1 and 2 D3 Waves 1, 2, 3, 4, 5 D4

The further addition of waves 3, 4, and 5 in D4 shortened intensification time in both instances by about an additional 20%. The relative magnitudes of the optimum amplitudes of these wave numbers are presented in EN 1-3.

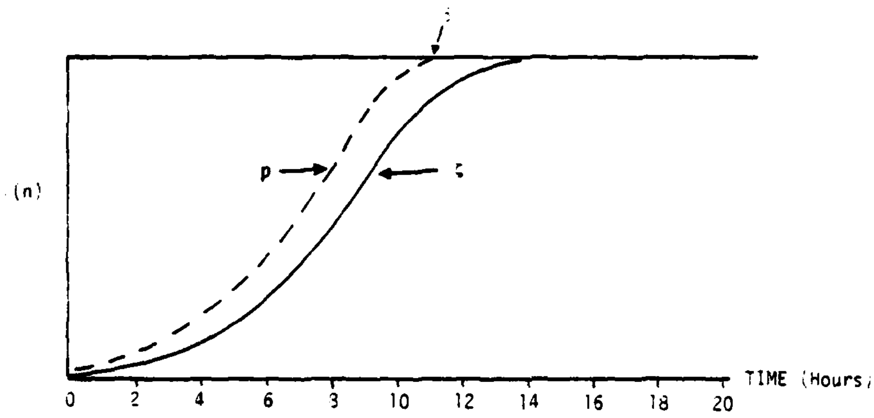
A-2. MUTUAL FORCING OF SPIRAL ASYMMETRIES IN THE DIVERGENCE AND VORTICITY FIELDS

The effect of the divergence field on the vorticity field and vice-versa is assessed in experiments DVAF 1-4, which stand for divergence vorticity asymmetry forcing. In DVAF1 the asymmetries in the vorticity field were forced by the asymmetries in the divergence field for wave numbers zero, one and two. From the graph of amplitude vs. time one can see that it took about 24 hours for the vorticity asymmetries to catch up to the divergence asymmetries with real progress only beginning after about 6 hours. In DVAF2, the reverse situation is much slower. Forcing of the divergence field by the vorticty field is not even partially successful until 40 hours have elapsed, and even after 60 hours the divergence amplitudes did not match the vorticity amplitudes.

In DVAF3 the pressure asymmetries were forced by the divergence asymmetries and responded substantially in eight hours, going to completion in 12. The response of the zero wave number or axially symmetric divergence field is a marked contrast with divergence regimes established and settled in DVAF4 within 12 hours in response to the axially symmetric vorticity field. This leads to the conclusion that two very different mechanisms are operative in the symmetric and asymmetric fields.

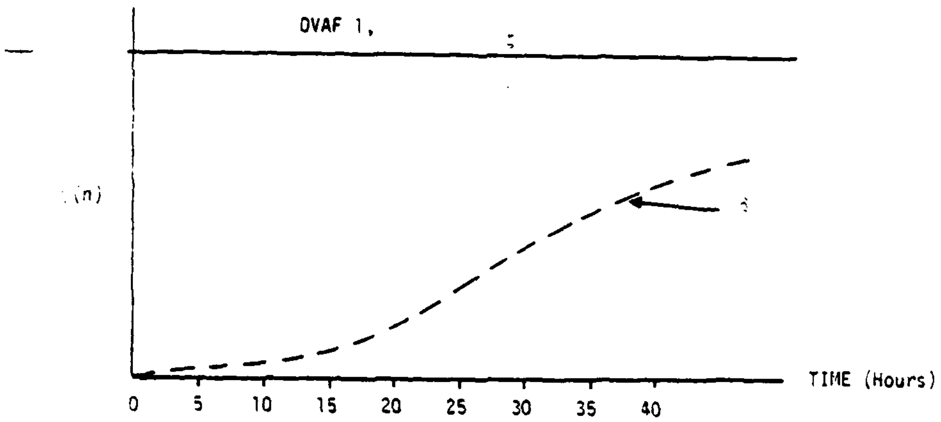
This reaffirms the quasi-independent nature of the two coexisting processes. The exact roles of each field symmetric and asymmetric, and their input, one into the other need to be investigated further.

Plots of Divergence-Vorticity Asymmetry Forcing (DVAF)

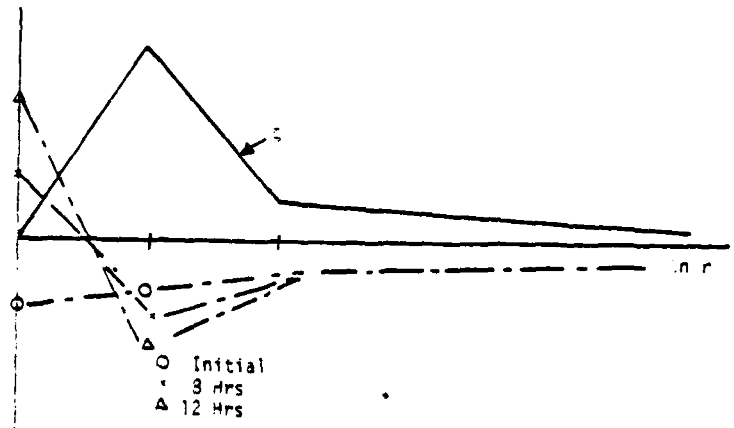


DVAF 1 — Forcing of Vorticity Asymmetries by Divergence Asymmetries.

DVAF 2 — Forcing of Pressure Asymmetry by Divergence Asymmetry.



DVAF 3 — Forcing of Divergence Asymmetries by Vorticity Asymmetries.



DVAF 4 — Behavior of the Axially Symmetric Divergence Field in Response to the Axially Symmetric Vorticity Field at $t = 0$, 8 and 12 hours.

A-3. THE ROLE OF THE RICHARDSON NUMBER AND CRITICAL ENSTROPHY IN THE FORMATION OF THE TYPHOON REGIMES

The role of both the Richardson number, R_i, and the enstrophy, $\zeta^2/2$ in the formation of both spiral and asymmetric regimes was assessed in a series of experiments, some of whose results re presented here. The Richardson number is defined as the ratio of work done against the buoyancy force to the kinetic energy in the vertical shear of the horizontal wind. When this ratio falls below 0.25, enough turbulent kinetic energy is available to overcome the stabilizing force by providing a consistent amount of work against it. In this case an inversion may be present in the lower atmosphere though not be enough to prevent "leaking" of air between the boundary layer and the upper atmosphere as a result of vertical turbulent transport. This in turn provides a feedback by lessening the intensity of the inversion until an equilibrium is established.

A-3.1 Richardson Number Experiment

Both asymmetric (waves number 1 and 2) and symmetric (wave number zero) distributions of the Richardson number are presented which resulted from setting the vertical velocity field contingent upon a critical Richardson number. This proviso was a necessary step in allowing the tropical depression to evolve into a full fledged typhoon. When the vertical velocity was allowed the Richardson number would not go much lower than 0.25 with an absolute minimum about 2 and a maximum approaching infinity in the center of the storm.

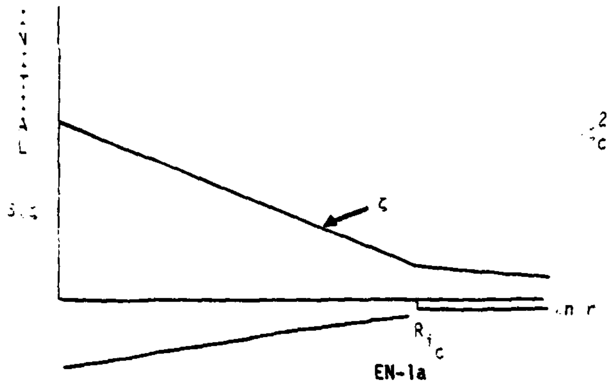
A-3.2

In EN-1 and EN-2 the role of critical enstrophy is assessed in the formations of the regimes in the vortex. The first experiment EN-1 deals with the axially symmetric distribution as a function of fixed wave numbers zero, one and two. It is seen that from an initial divergence and vorticity state shown in EN-1a, the critical Richardson value migrates inward in the storm crowding vorticity and divergence ahead of it. After 18 hours a critical enstrophy is reached which is never exceeded and then the central vorticity and convergence values begin to fall. In 22 hours the eye begins to form as the convergence in the center converts to divergence and the winds assume a calmer

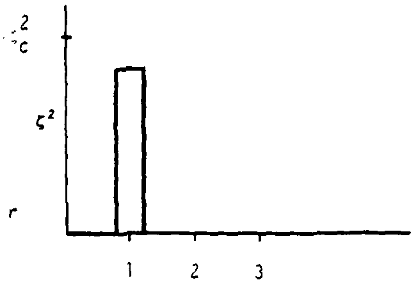
configuration. At 26 hours the eye is fully developed and the storm has tightened.

In EN-2 the critical enstrophy is tested against the wave number for the same time periods. This allows the enstrophy to cascade into the smaller waves or higher wave numbers with the exception of wave number one which contributes considerably to the asymmetric appearance of the storm. The enstrophy occurs primarily in the even waves with 80% of the vorticity distributed between waves numbers one and two. It seems that once a critical enstrophy is reached, any excess goes into the higher wave number with a consequent greater possibility of bleeding off into turbulent dissipation. Hence, frictional dissipation seems to act as a break on enstrophy accumulation in the higher numbers, allowing the storm to have more of a simple pinwheel structure.

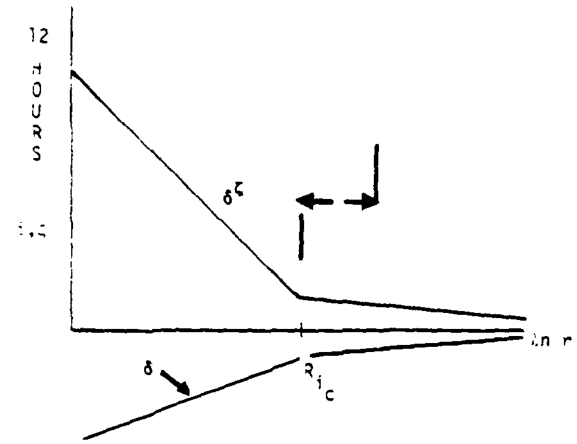
Plots of Critical Enstrophy vs. Vorticity and Divergence Distribution



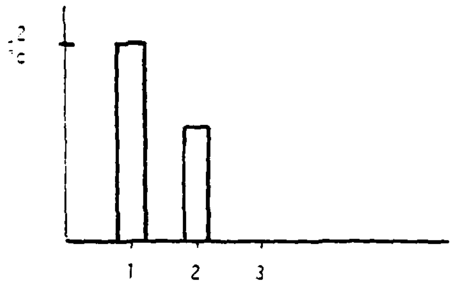
EN-1a - Initial State of Axially Symmetric Distribution of δ and ζ .



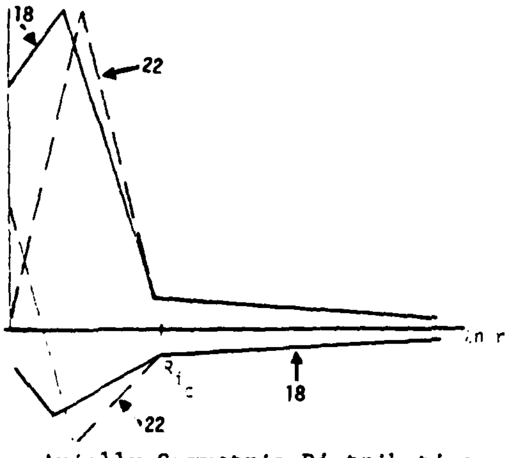
EN-1b — Initial Distribution of Entrophy in Waves with Prominence in Wave #1.



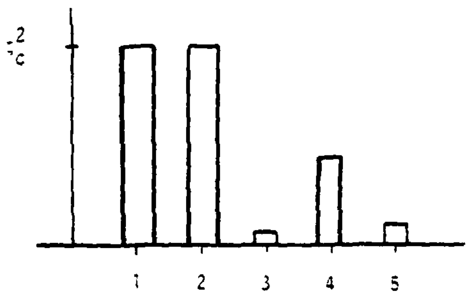
EN-2a — Migration of R_i Inward Causing Crowding of δ and ζ Inward.



EN-2b — Cascade of Enstrophy from Wave #1 to Wave #2.



EN-3a — Axially Symmetric Distribution of δ and ζ at 18 and 22 hours Showing Eye Development.



EN-3b — Further Cascade of Enstrophy Into Waves 3-5 with a Maximum in Wave #4.

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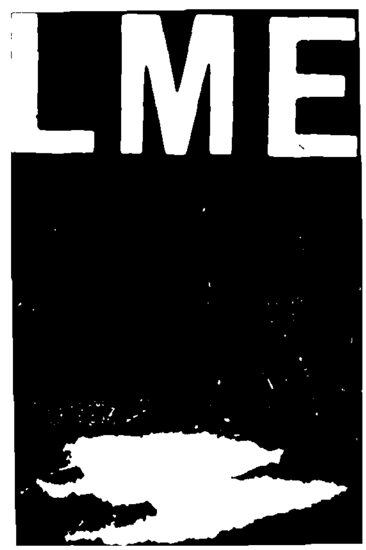
Trout, Robert, 1979: personal communication.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